POLITECNICO DI TORINO

# DESIGN AND ANALYSIS OF ULTRA-WIDEBAND RAMAN AMPLIFIER CONSIDERING FULL AND PARTIAL LOADS

**A. MARGARETH ROSA BRUSIN**[1], UIARA C. DE MOURA[2], DARKO ZIBAR[2] AND ANDREA CARENA[1]

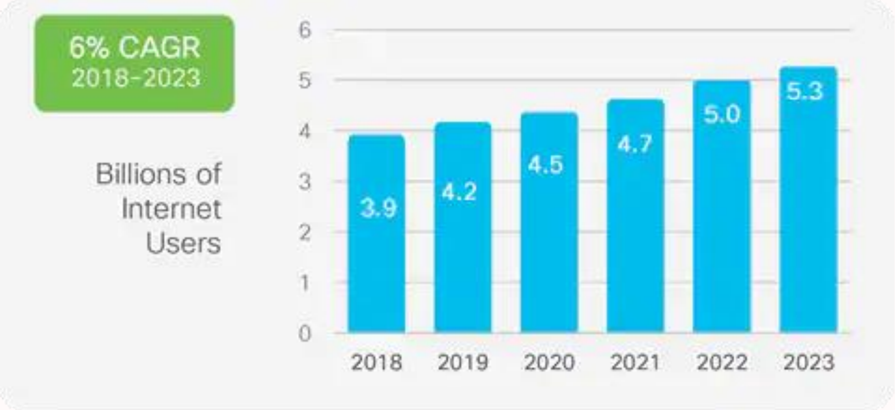
1. OPTCOM Optical Communications Group – Politecnico di Torino, Torino – ITALY, ann.rosabrusin@polito.it
2. DTU Fotonik – Technical University of Denmark, Lyngby – DENMARK

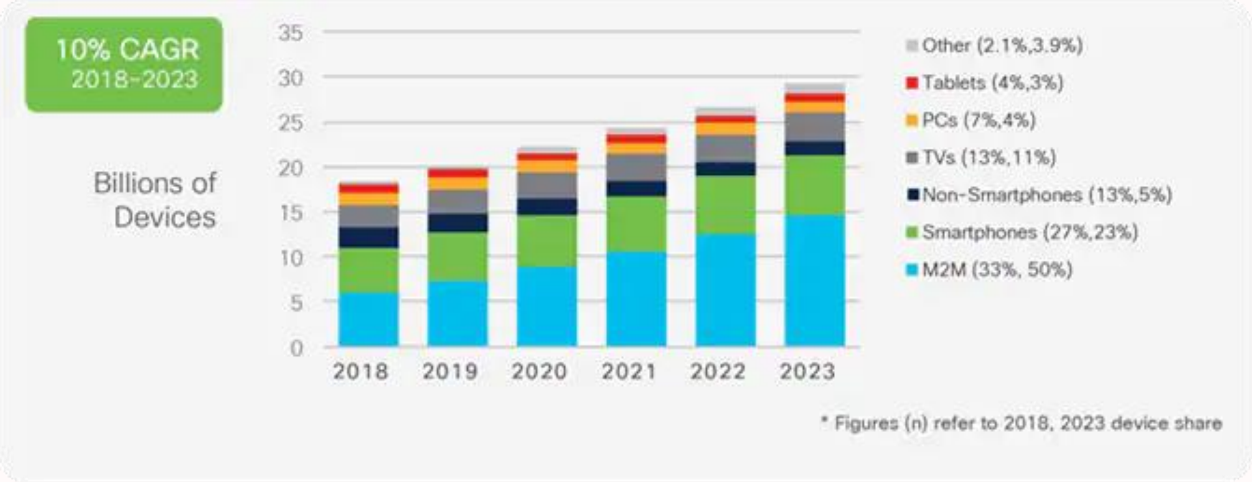
# OUTLINE

- Motivation and scenario
- Raman amplifier design
- Raman amplification analysis

# MOTIVATION AND SCENARIO

# Face the increasing Internet demand




**Source: Cisco Annual Internet Report, 2018–2023**
https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

- To face the continuously growing internet data traffic, the increasing capacity demand and the new requirements of 5G networks
  - Improve digital signal processing (DSP) techniques
  - Improve transmission medium
  - Exploit space division multiplexing (SDM)
  - Extend transmission band from C-band towards multi-bands (O,E,S,C and L)
    - Exceeding the optimal working region of Erbium Doped Fiber Amplifiers (EDFAs) covering C+L-band

# Extend transmission band

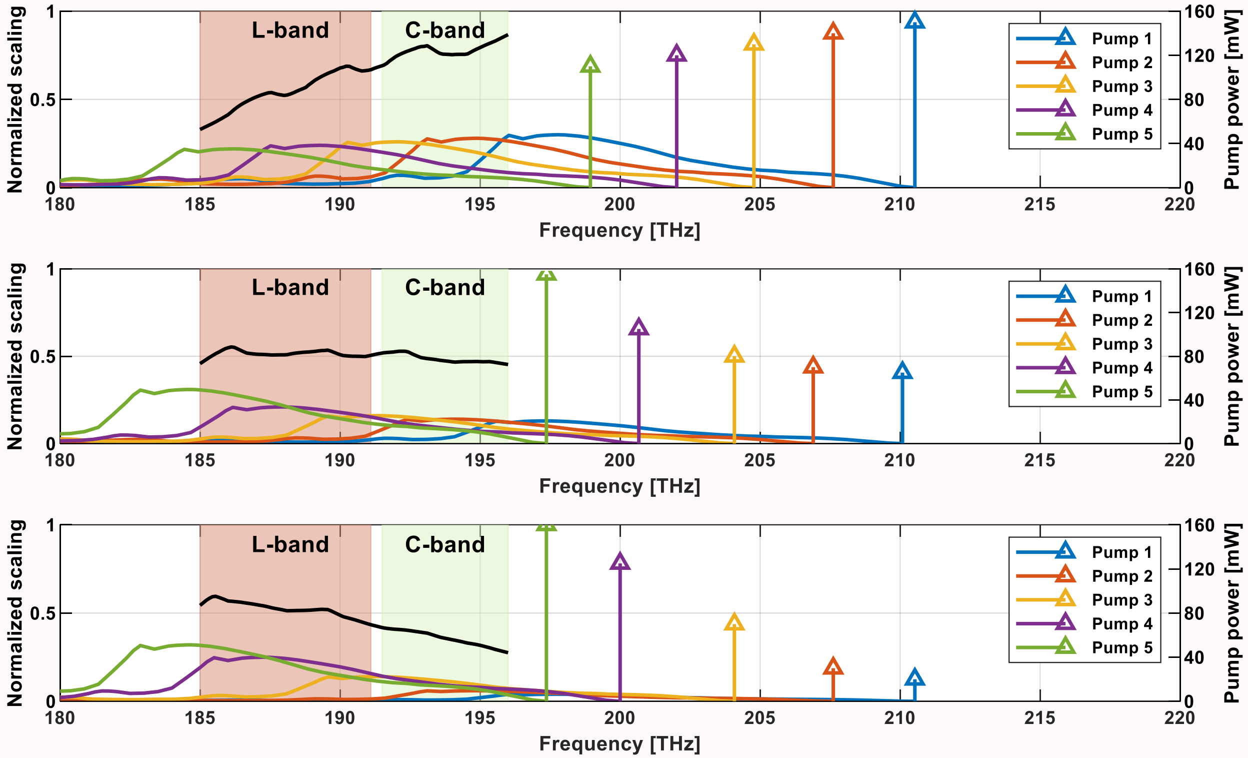
- Possible amplification schemes when moving from C-band towards multi-bands
  - Hybrid Erbium/Bismuth Doped Fiber Amplifier + Raman Amplifier (xDFA+RA)
  - Pure Raman Amplifier (RA)
  - Semiconductor Optical Amplifier (SOA)

- In particular, RAs are gaining a lot of attention thanks to
  - Availability of ultra-wide amplification over multi-bands (O, E, S, C and L bands)
  - Possibility to provide flexible and programmable gains by properly adjusting pump powers and frequencies
  - Lower noise figure than other amplification schemes in case of distributed Raman amplification along the optical span

# RAMAN AMPLIFIER DESIGN

# Design of a Raman Amplifier

- By a proper tuning of Raman pumps (powers and frequencies) it is possible to obtain a desired gain
  - Flat gain over the transmission bands
  - Tilted or arbitrary gains when used as a gain flattening tool to correct the tilt due to the inter-channel stimulated Raman scattering (ISRS) effect (in particular in a multi-band scenario) or the EDFA tilt



# Strategies to design a Raman Amplifier

- It is a challenging optimization problem because of the nonlinear ordinary differential equations (ODEs) that needs to be solved for different boundary conditions (both begin and end of the optical span link)
- Different strategies have been studied
  - Genetic Algorithms (GA)
  - Machine Learning (ML)
  - Other optimization strategies (e.g. Sequential Least Squares Programming (SLSQP) algorithm)

**Efficient use of hybrid Genetic Algorithms in the gain optimization of distributed Raman amplifiers**

B. Neto[1,2], A. L. J Teixeira[1,3], N. Wada[4], P. S. André[1,2]
[1] Instituto de Telecomunicações, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
[2] Departamento de Física, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
[3] Departamento de Electrónica, Telecomunicações e Informática, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
[4] National Institute of Information and Communications Technology, 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795 Japan
*Corresponding author: bneto@av.it.pt

**Optimization of Distributed Raman Amplifiers Using a Hybrid Genetic Algorithm With Geometric Compensation Technique**

Gustavo C. M. Ferreira,[1] S. P. N. Cani,[2] M. J. Pontes,[1] and M. E. V. Segatto[1]
[1] Department of Electrical Engineering, Federal University of Espírito Santo, Vitória 29060-970, Brazil
[2] Department of Electrical Engineering, Federal Institute of Espírito Santo, Vitória 29040-780, Brazil

DOI: 10.1109/JPHOT.2011.2140366

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 38, NO. 4, FEBRUARY 15, 2020

**Inverse System Design Using Machine Learning: The Raman Amplifier Case**

Darko Zibar, Ann Margareth Rosa Brusin, Uiara C. de Moura, Francesco Da Ros, Vittorio Curri, and Andrea Carena

JOURNAL OF LIGHTWAVE TECHNOLOGY 1

**Model-aware Deep Learning Method for Raman Amplification in Few-Mode Fibers**

Gianluca Marcon, Andrea Galtarossa, *Fellow, IEEE/OSA*, Luca Palmieri, *Member, IEEE/OSA*, and Marco Santagiustina, *Member, IEEE*

IOP Publishing Journal of Optics
J. Opt. 20 (2018) 025702 (6pp) https://doi.org/10.1088/2040-8986/aaa2a6

**Efficient design of gain-flattened multi-pump Raman fiber amplifiers using least squares support vector regression**

Jing Chen, Xiaojie Qiu, Cunyi Yin and Hao Jiang
College of Electrical Engineering and Automation, Fuzhou University, Fuzhou 350116, People's Republic of China

ICTON 2019 We.B7.3

**Machine Learning for Ultrawide Bandwidth Amplifier Configuration**

Maria Ionescu*
Nokia Bell Labs Paris-Saclay, Nozay, 91620, France
*e-mail: maria.ionescu@nokia-bell-labs.com

2020 International Conference on Optical Network Design and Modeling (ONDM)

**Softwarized and Autonomous Raman Amplifiers in Multi-Band Open Optical Networks**

Giacomo Borraccini*(1), Alessio Ferrari(1), Stefano Straullu(2), Antonino Nespola(2), Andrea D'Amico(1), Stefano Piciaccia(3), Gabriele Galimberti(3), Alberto Tanzi(3), Silvia Turolla(3), Vittorio Curri(1)
(1) Politecnico di Torino, Turin, Italy; (2) LINKS foundation, Turin, Italy; (3) Cisco Photonics, Vimercate, Italy
*giacomo.borraccini@polito.it

# Machine Learning-based RA design over C-band

JOURNAL OF LIGHTWAVE TECHNOLOGY

[1] Experimental characterization of Raman amplifier optimization through inverse system design

Uiara C. de Moura, Francesco Da Ros, A. Margareth Rosa Brusin, Andrea Carena, and Darko Zibar

**EXPERIMENTAL SETUP**

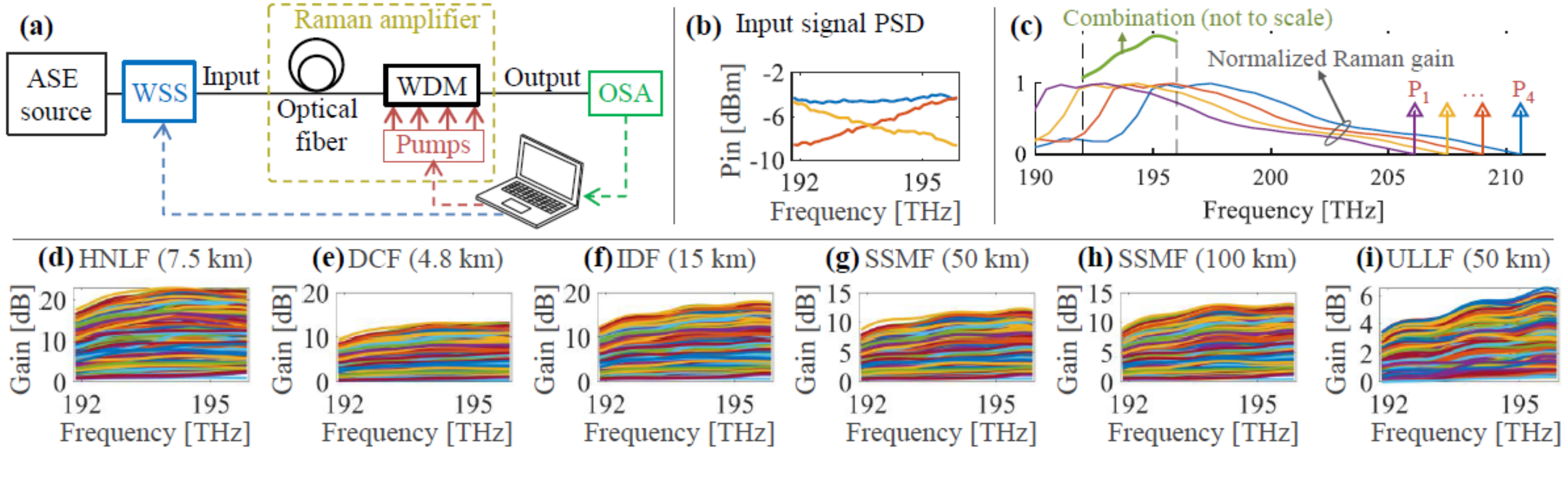
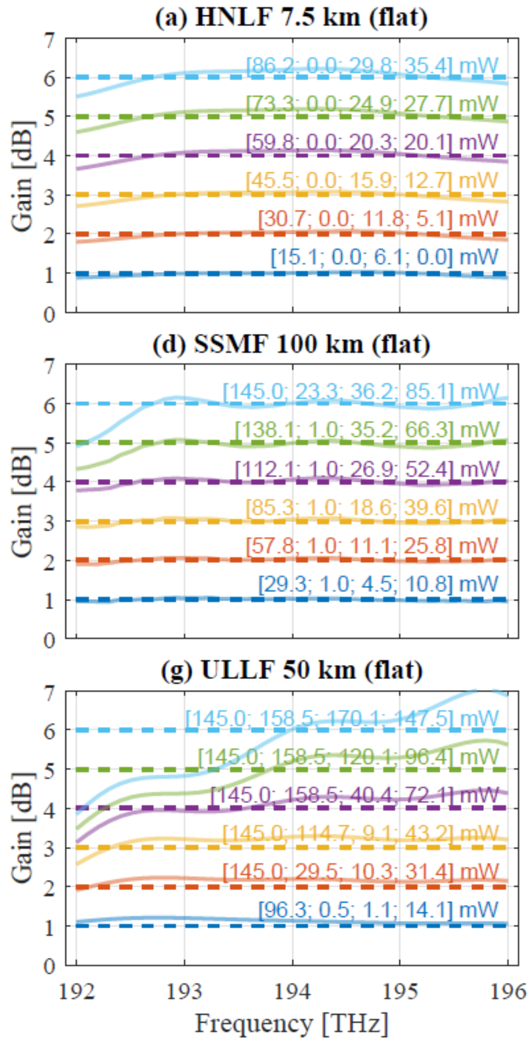



Fig. 1. (a) Experimental setup to capture the data–set for the NN training and further validations showing the measured on–off gain–profiles for each fiber types/length; (b) some examples of input signal power spectral density (PSD) profiles; (c) normalized Raman gain coefficients for each pump laser; and measured gain–profiles for (d) HNLF, (e) DCF, (f) IDF, (g) SSMF (50 km), (h) SSMF (100 km), and (i) ULLF.

[1] U. C. de Moura, F. Da Ros, A. M. Rosa Brusin, A. Carena and D. Zibar, "Experimental characterization of Raman amplifier optimization through inverse system design," in *Journal of Lightwave Technology*, doi: 10.1109/JLT.2020.3036603.

**RESULTS**




OPTCOM

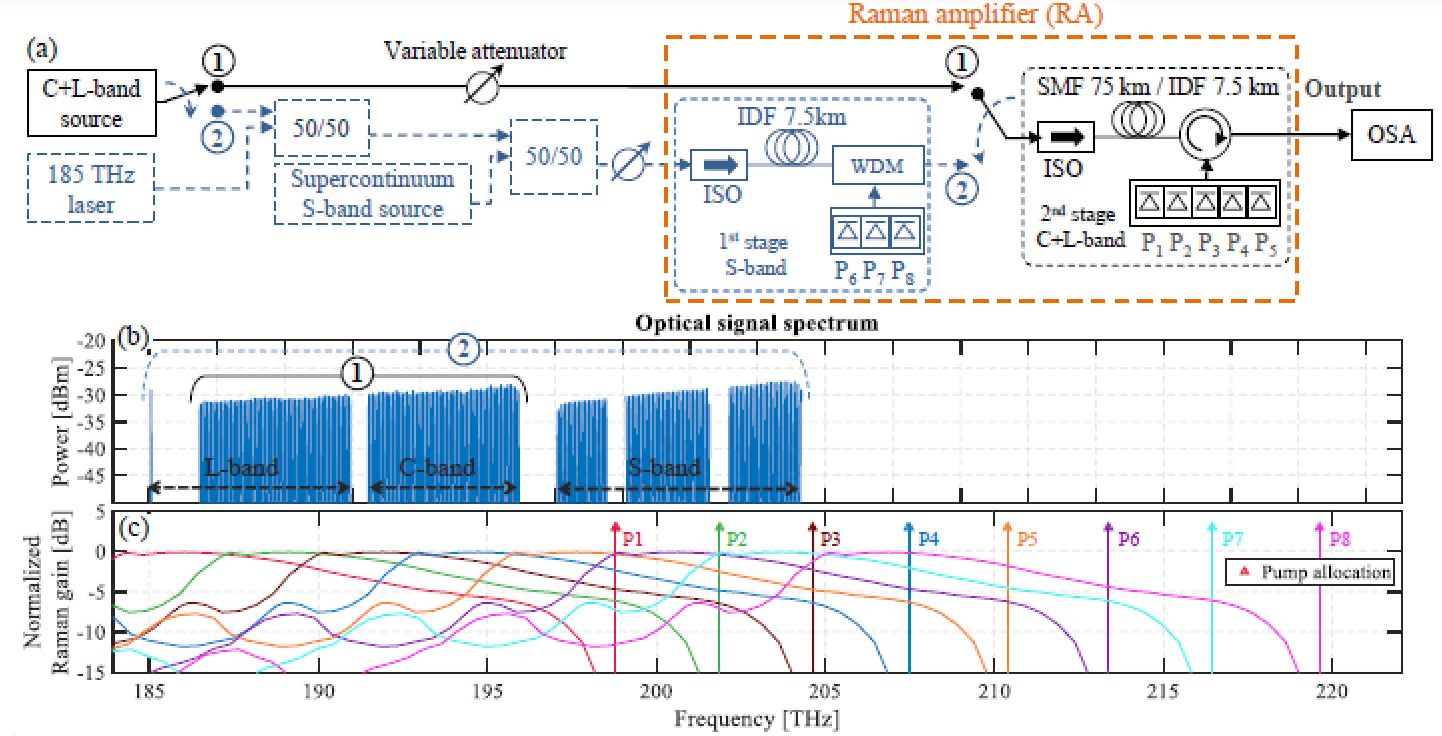
# Machine Learning-based RA design over S+C+L-band

JOURNAL OF LIGHTWAVE TECHNOLOGY

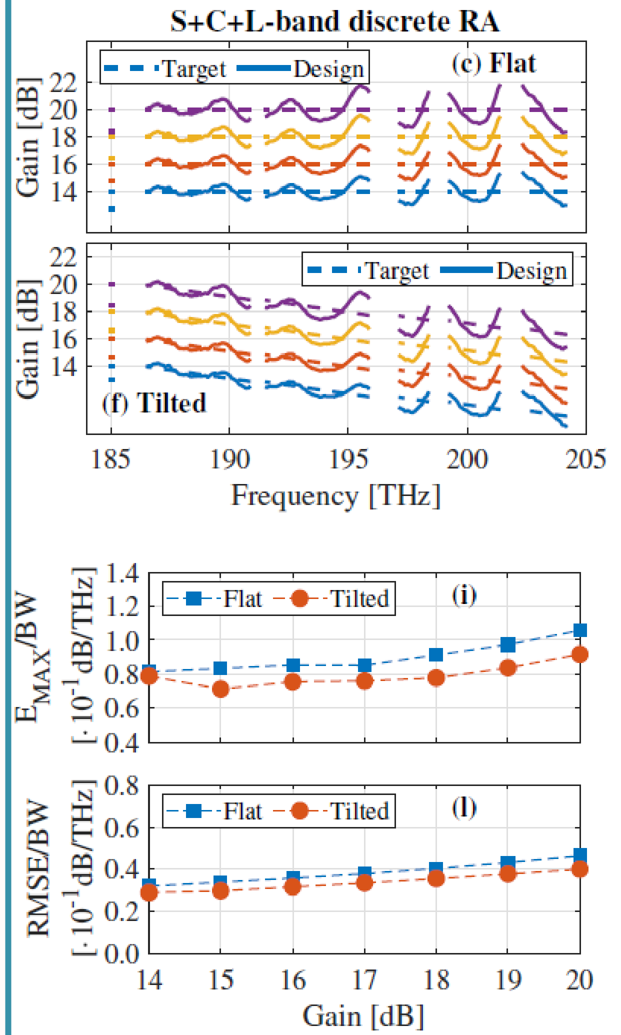
## [2] Multi–band programmable gain Raman amplifier

Uiara Celine de Moura, Md Asif Iqbal, Morteza Kamalian, Lukasz Krzczanowicz, Francesco Da Ros, Ann Margareth Rosa Brusin, Andrea Carena, Wladek Forysiak, Sergei Turitsyn, and Darko Zibar

**EXPERIMENTAL SETUP**




**RESULTS**




**(c),(f): Predicted and target flat and tilted (on–off) gain profiles with respect to frequency**
**(i): Maximum error of gain prediction with respect to total bandwidth**
**(l): Root-mean-square-error of gain prediction with respect to total bandwidth.**

[2] U. C. De Moura et al., "Multi-band programmable gain Raman amplifier," in *Journal of Lightwave Technology*, doi: 10.1109/JLT.2020.3033768.

# RAMAN AMPLIFICATION ANALYSIS

# Machine Learning for Raman Amplification Analysis

- In general, Raman amplification based on stimulated Raman scattering (SRS) is modeled by a set of ODEs describing the power evolution along frequency and spatial positions [3]:
  - $\frac{dP_{s,i}}{dz} = -\alpha_s P_{s,i} + C_R(\lambda_{s,i}, \lambda_{p,j})[P^{+}_{p,j} + P^{-}_{p,j}]P_{s,i}$
  - $\pm\frac{dP^{\pm}_{p,j}}{dz} = -\alpha_p P^{\pm}_{p,j} - \left(\frac{\lambda_{s,i}}{\lambda_{p,j}}\right) C_R(\lambda_{s,i}, \lambda_{p,j}) P_{s,i} P^{\pm}_{p,j}$
  - $\pm\frac{dP^{\pm}_{A,i}}{dz} = -\alpha_A P^{\pm}_{A,i} + C_R(\lambda_{A,i}, \lambda_{p,j}) P_{p,j} P^{\pm}_{A,i} + C_R(\lambda_{A,i}, \lambda_{p,j})[1 + \eta(T)] h\nu_{A,i} B_{ref} P_p$

  with $i$ identifying the signal channel for $i = \{1, \dots, n_{ch}\}$ and $j$ identifying the pump for $j = \{1, \dots, n_{pumps}\}$

[3] J. Bromage, '*Raman Amplification for Fiber Communications Systems*', Journal of Ligthwave Technology, vol. 22, no. 1, pp. 79-93, 2004.

- Not practical in future optical networks providing
  - Self-resource allocation
  - Self-automation for fast routing
  - Adaptability to partial traffic allocation due to different spectral loads (no longer almost static traffic only)

**Machine Learning as ultra-fast tool to predict Raman gain and ASE noise profiles**

# Neural Networks Aware of Spectral Loads

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 38, NO. 23, DECEMBER 1, 2020

[4]

## Introducing Load Aware Neural Networks for Accurate Predictions of Raman Amplifiers

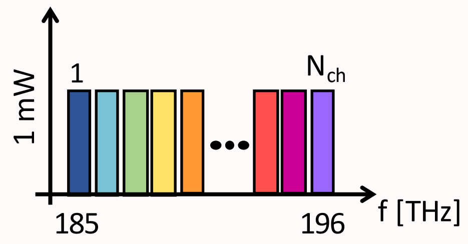
A. Margareth Rosa Brusin, Uiara C. de Moura, Vittorio Curri, Darko Zibar, and Andrea Carena

[4] A. M. Rosa Brusin, U. C. de Moura, V. Curri, D. Zibar and A. Carena, "Introducing Load Aware Neural Networks for Accurate Predictions of Raman Amplifiers," in *Journal of Lightwave Technology*, vol. 38, no. 23, pp. 6481-6491, 1 Dec.1, 2020, doi: 10.1109/JLT.2020.3014810.

[5] GNPy, [Online]. Available: https://github.com/Telecominfraproject/ooptgnpy

**INPUT**

**Wavelength Division Multiplexing (WDM) comb**

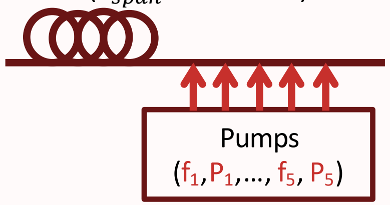



- C+L band: $f \in [185,196]$ THz
- $N_{ch}$ = 220 channels (50 GHz frequency slot spacing, 1mW power per slot)

- **Full load** data-set
- **Partial load** data-set

**DISTRIBUTED RAMAN AMPLIFIER**

SMF ($L_{span} = 100\ km$)

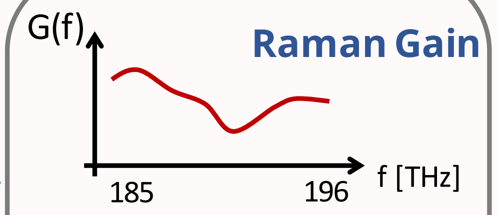


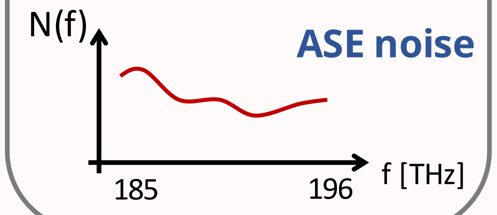

**NUMERICAL RAMAN SOLVER [5]**

**Pump frequencies**:
$f_1$ = 210.37 THz, $f_2$ = 207.14 THz, $f_3$ = 204.01 THz, $f_4$ = 200.97 THz, $f_5$ = 198.03 THz

**Pump powers**:
$P_i \in [0,250]mW$ with $i = 1, \ldots 5$

**OUTPUT**



# Dataset generation: WDM comb

- 220 channels of 50 GHz carrying 1 mW of power
  - Full load: all the frequency slots are ON (already considered in [6])
  - Partial load: each frequency slot can be ON or OFF
- In partial load scenario: $2^{220}$ possible combinations + pump power arbitrariness

TOO LARGE!

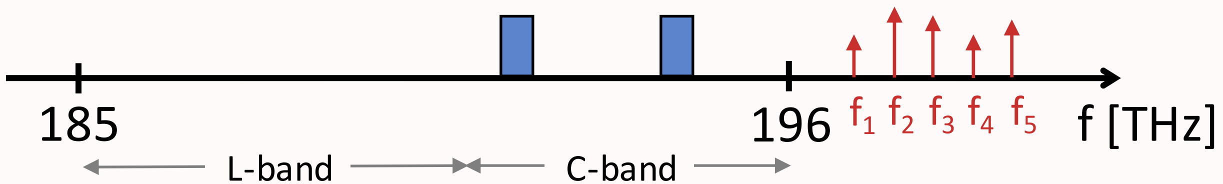
SOLUTION

- 10 adjacent frequency slots grouped together to form a sub-band
- Each sub-band is 500 GHz wide and can assume two states: ON or OFF
- Total of 22 sub-bands over the entire 11 THz C+L-band
  - 12 sub-bands in the L-band
  - 10 sub-bands in the C-band

[6] A. M. Rosa Brusin, V. Curri, D. Zibar and A. Carena, '*An Ultra-Fast Method for Gain and Noise Prediction of Raman Amplifiers*', ECOC, Dublin, Ireland, September 2019, paper Th1C3.

# Dataset generation: Classes of datasets

- Classes of data-sets:
  - Class C: only sub-bands in C-band → from 2 to10 sub-bands



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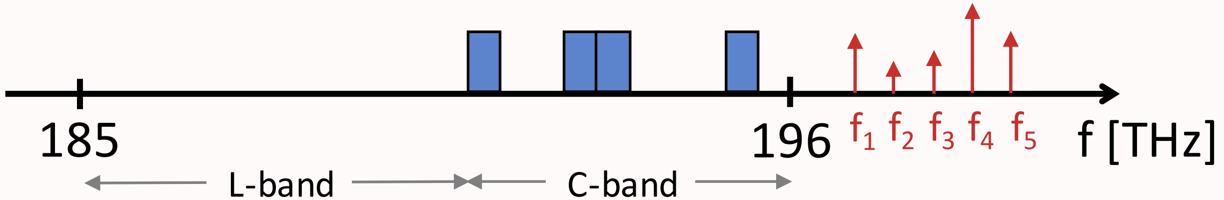

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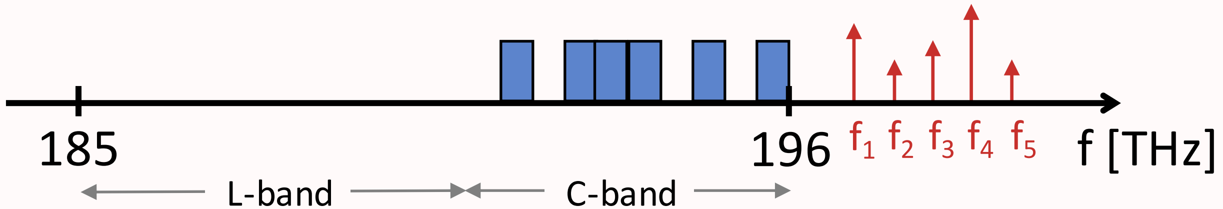

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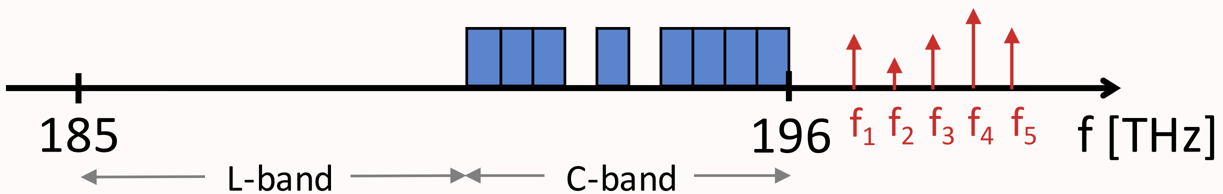

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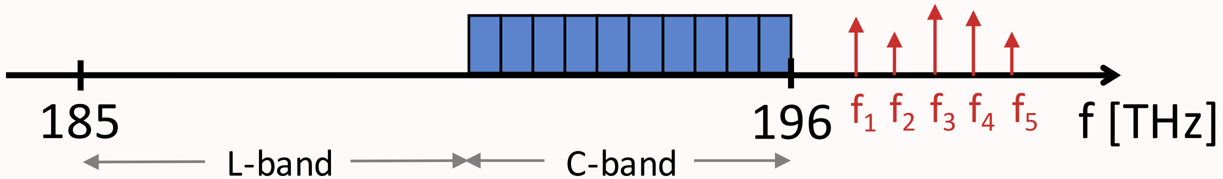
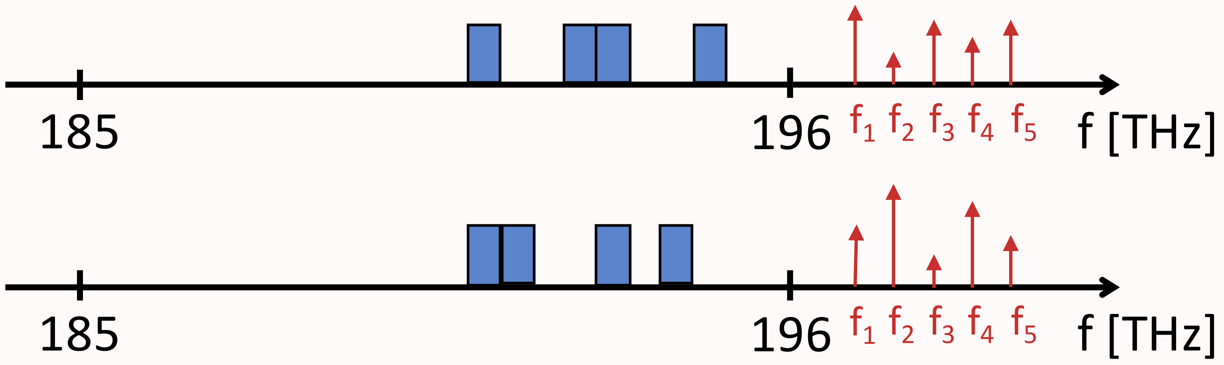



e.g. Sub-class: 4 sub-bands ON

- Within each class we can identify sub-classes, corresponding to the number of sub-bands turned ON



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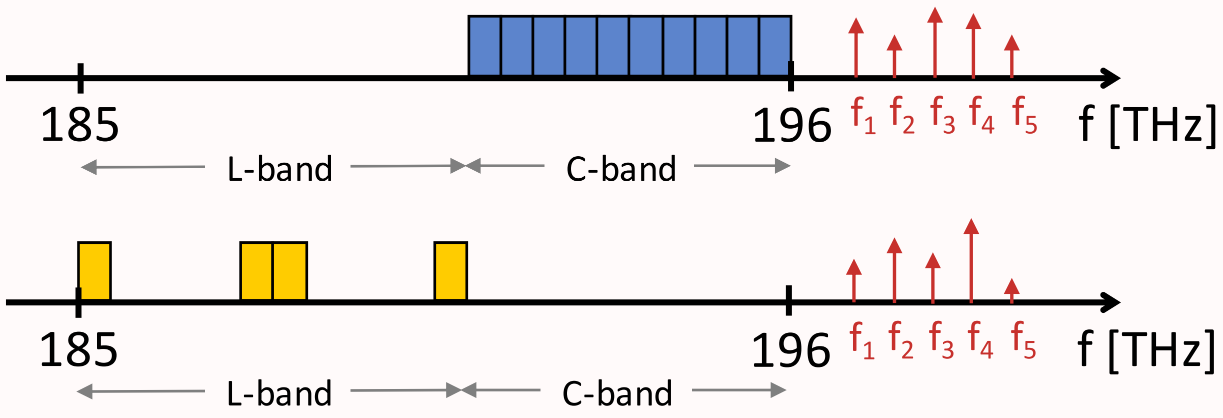
- Classes of data-sets:
  - Class C: only sub-bands in C-band → from 2 to10 sub-bands
  - Class L: only sub-bands in L-band → from 2 to12 sub-bands

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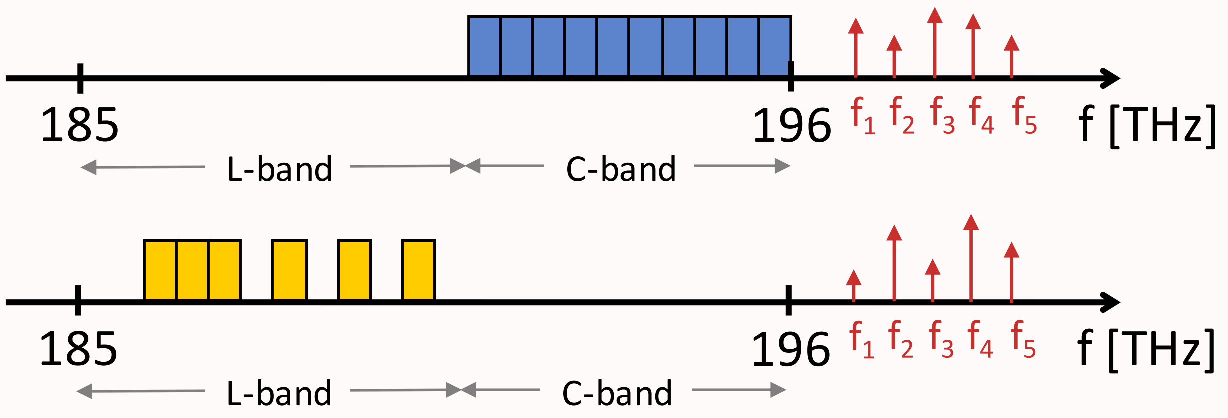


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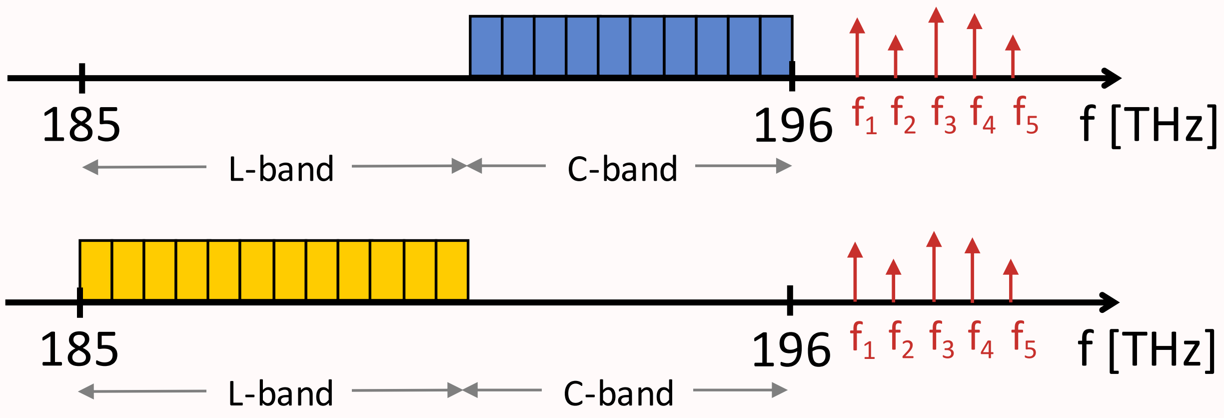


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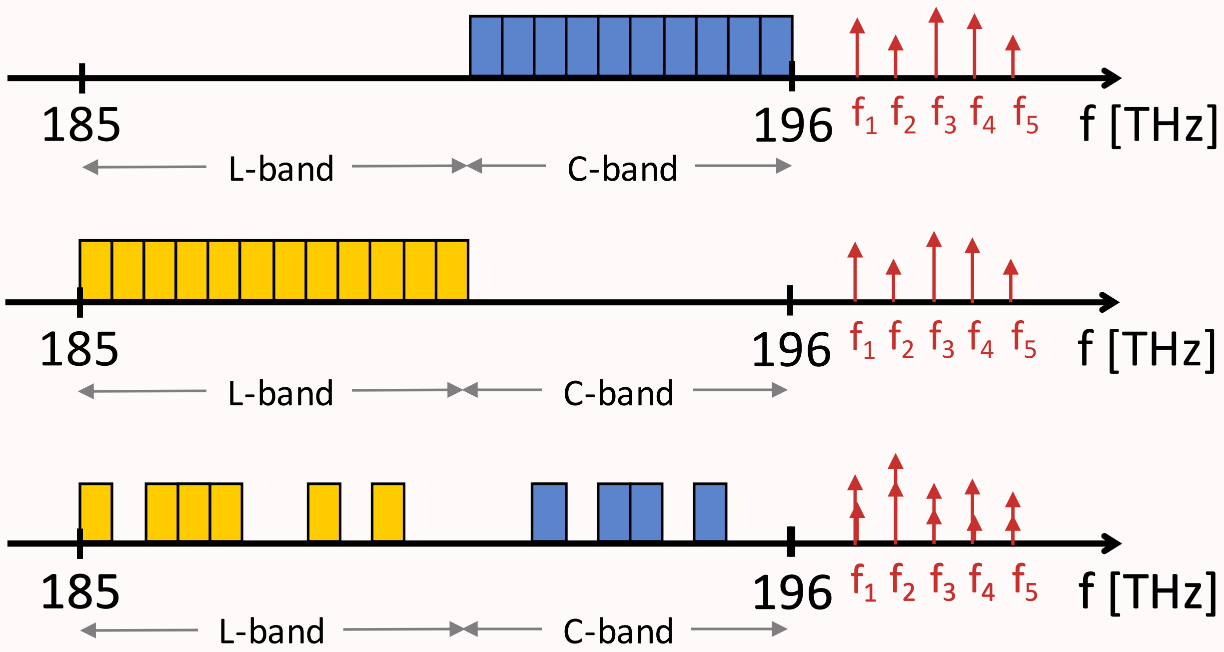
  - Class C+L: sub-bands in C+L-band → from 2 to 22 sub-bands (i.e. full load)
- Within each class we can identify sub-classes, corresponding to the number of sub-bands turned ON




OPTCOM

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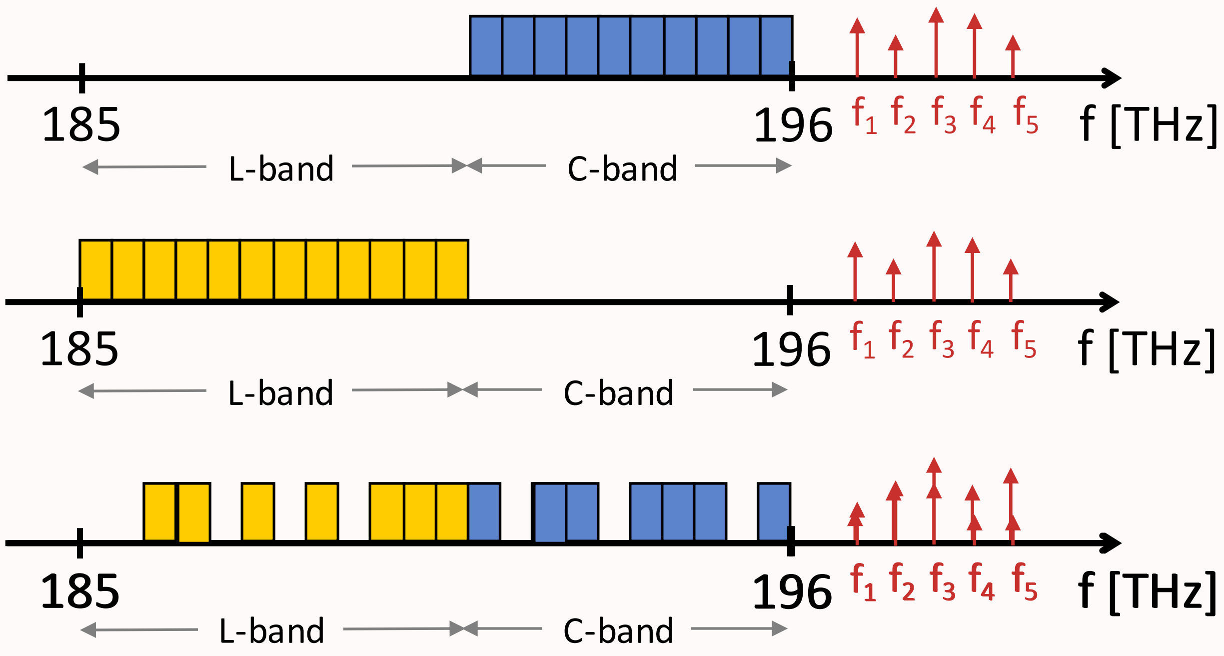

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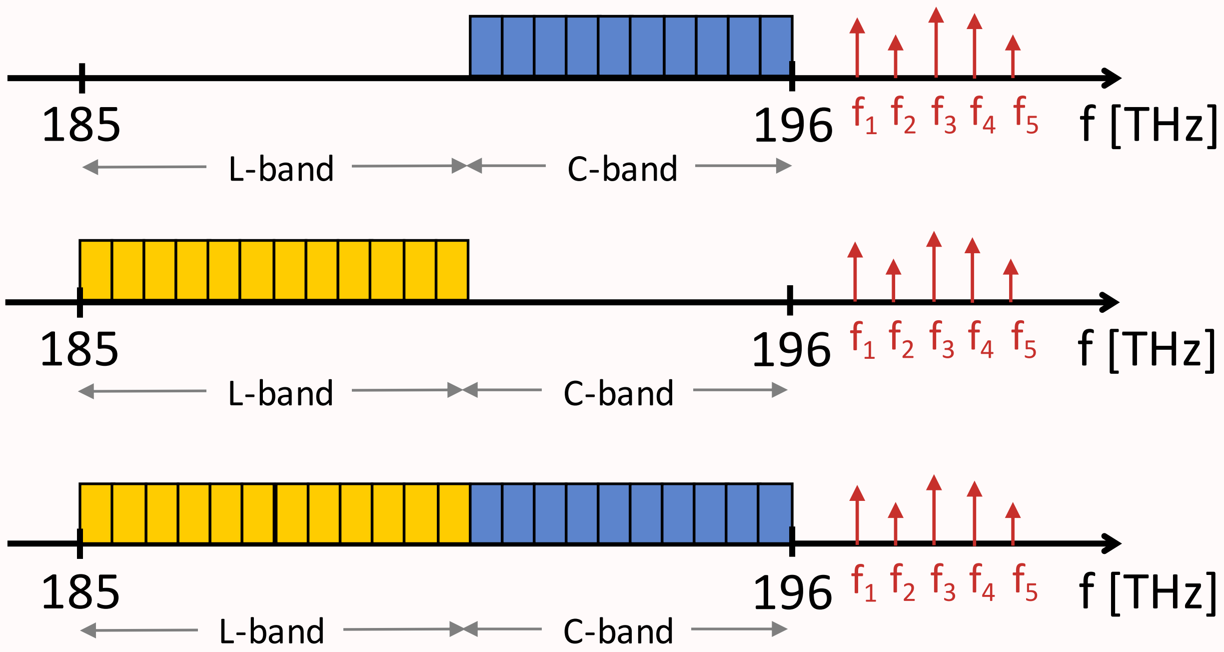


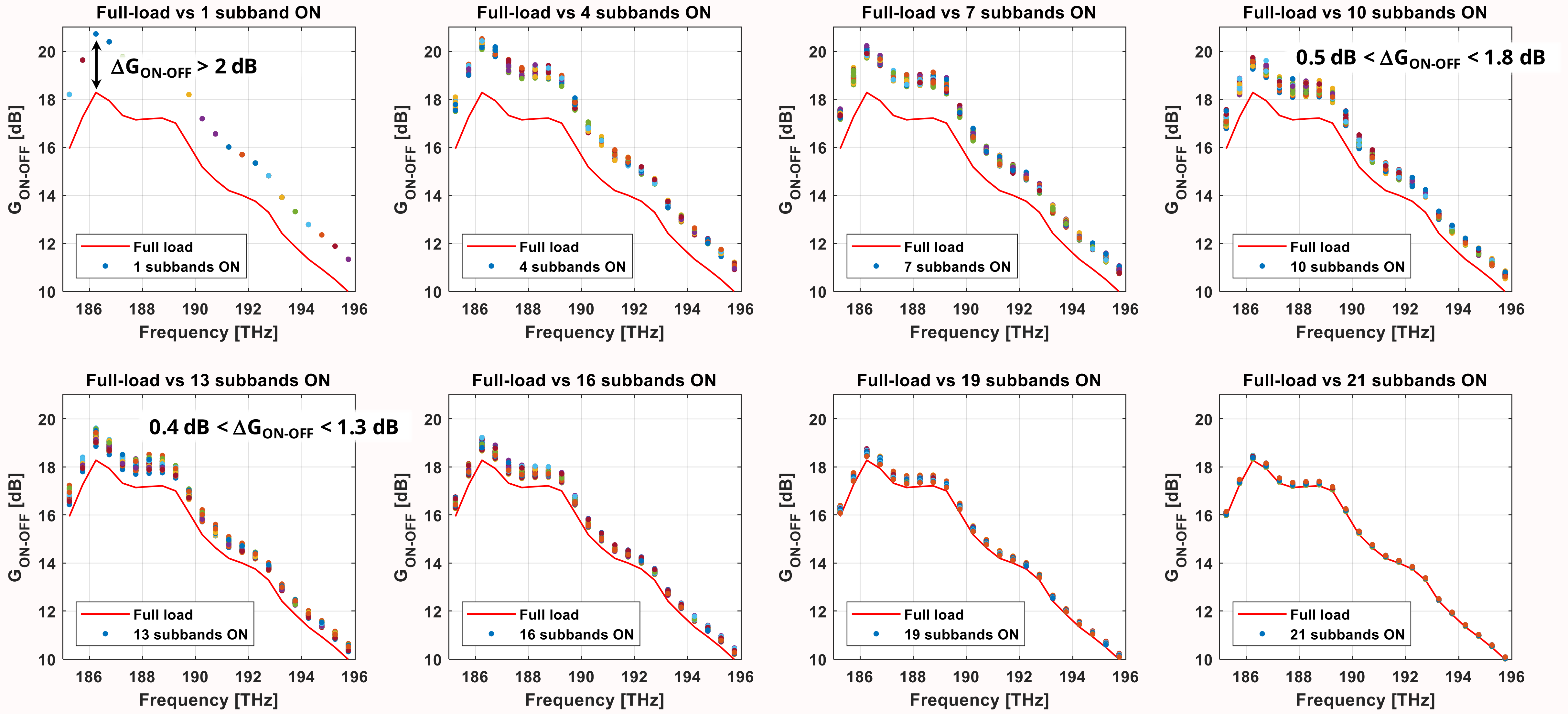

- Full load data-set: 5000 cases for Class C+L with 22 sub-bands ON
- Partial load data-set: 500 cases for each class and sub-class, for a total of 11000 cases

# Effect of partial loads on Raman gain and ASE noise profiles

- To analyze the effect of different partial loads with respect to a fully loaded input spectrum we consider the following scenario
  - C+L band: $f \in [185{,}196]$ THz
  - Fixed pump powers and frequencies
    - $f_{p,1\ldots5} = [210.51\ \ 207.28\ \ 204.15\ \ 201.11\ \ 198.16]$ THz
    - $P_{p,1\ldots5} = [246.7\ 237.7\ 194.2\ 192.7\ 168.8]$ mW
- We generate the Raman gain (ON-OFF gain) and the ASE noise profiles for the **full load** case
- To emulate the **partial loads**, for each sub-class (number of sub-bands ON from 1 to 21) we generate 100 different load configurations with randomly selected sub-band position in the entire transmission band
- Then considering these different partial loads, we generate the corresponding gain and noise profiles by means of the numerical Raman solver

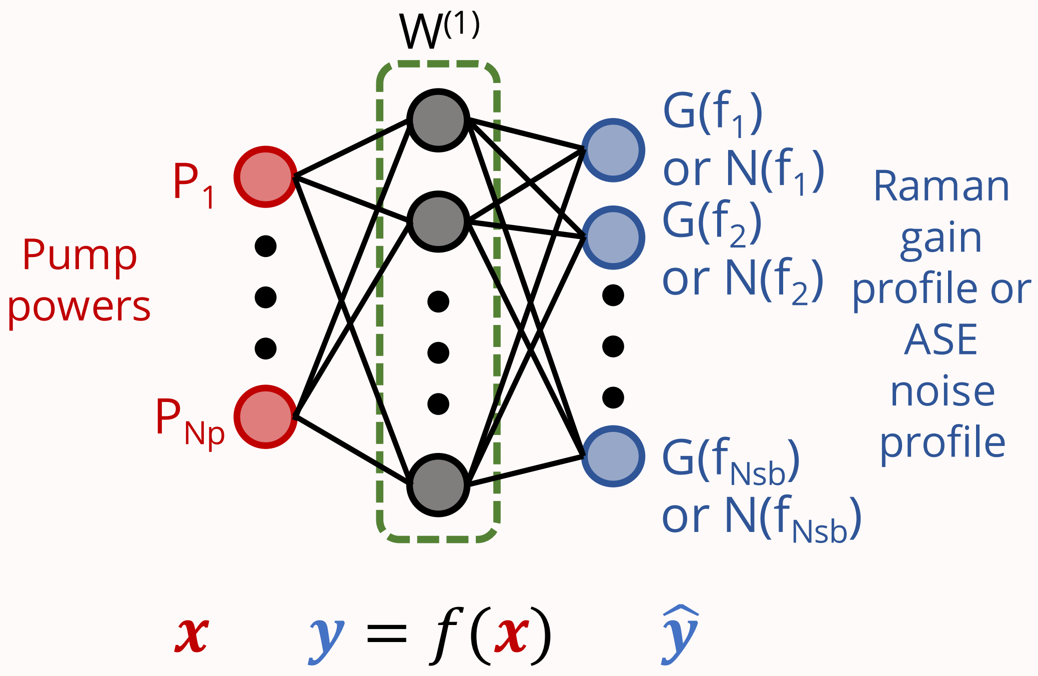
OPTCOM

# Example of effects of partial loads on Raman gain profiles

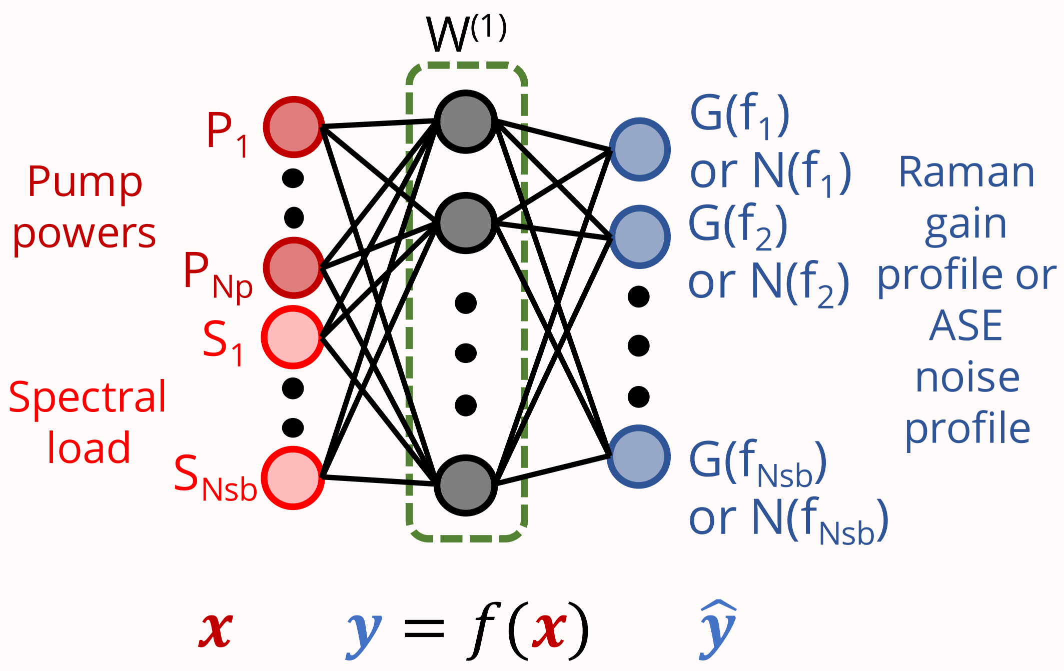


# Machine Learning Framework

## Load Unaware NN (LU-NN)




## Load Aware NN (LA-NN)




- Two separated data-sets are considered: **training** data-set and **testing** data-set, for the two stages of the process

# Neural Network Validation Process

Input data

$\left[P_1, P_2, \ldots, P_{N_p}\right]$

Or

$\left[P_1, P_2, \ldots, P_{N_p}, S_1, S_2, \ldots, S_{N_{sb}}\right]$

LU-NN

LA-NN

NUMERICAL RAMAN SOLVER

TRAINED NEURAL NETWORK

Target profile $Y_{target}$

Predicted profile $Y_{pred}$

**COMPARISON**

Maximum error:

$$Error_{MAX} = \max_{i\,\epsilon\,\{1,N_{sb}\}} \left|Y_{pred,i}(f) - Y_{target,i}(f)\right|$$

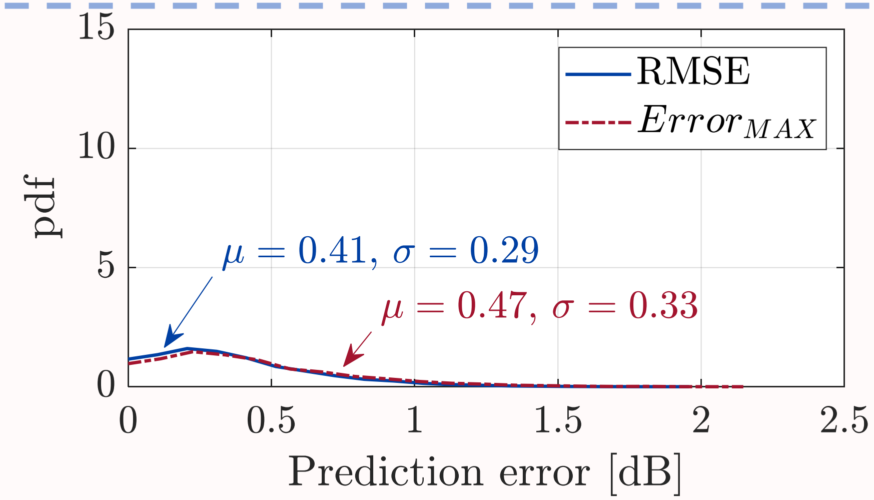
Root-mean-square-error (RMSE):

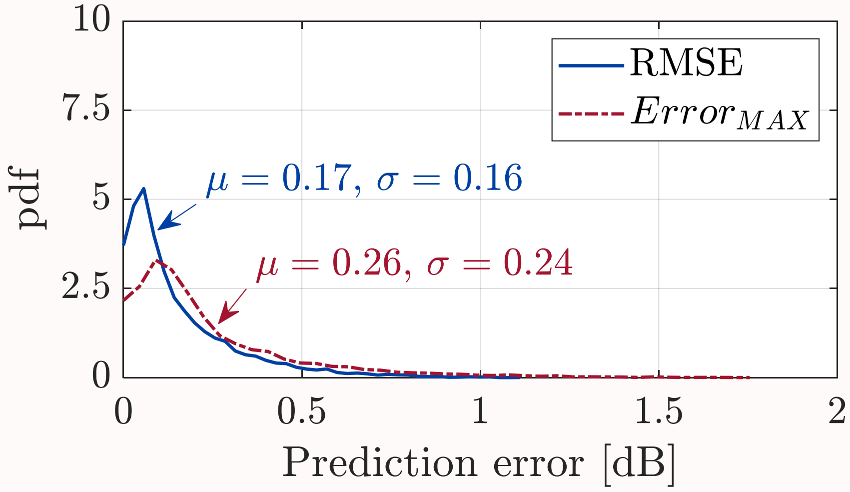
$$RMSE = \sqrt{\frac{1}{N_{sb}} \sum_{i=1}^{N_{sb}} \left(Y_{pred,i}(f) - Y_{target,i}(f)\right)^2}$$

# Testing Results: LU-NN vs LA-NN

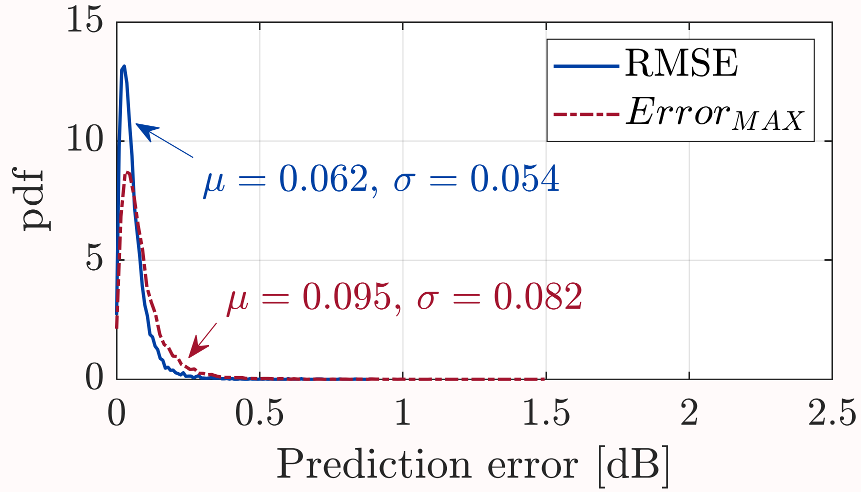
**RAMAN GAIN PREDICTION** | **ASE NOISE PREDICTION**

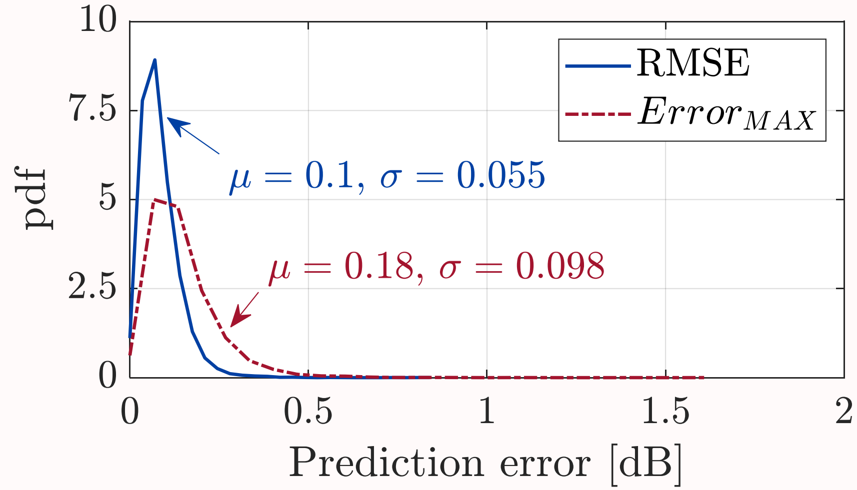
**LU-NN**



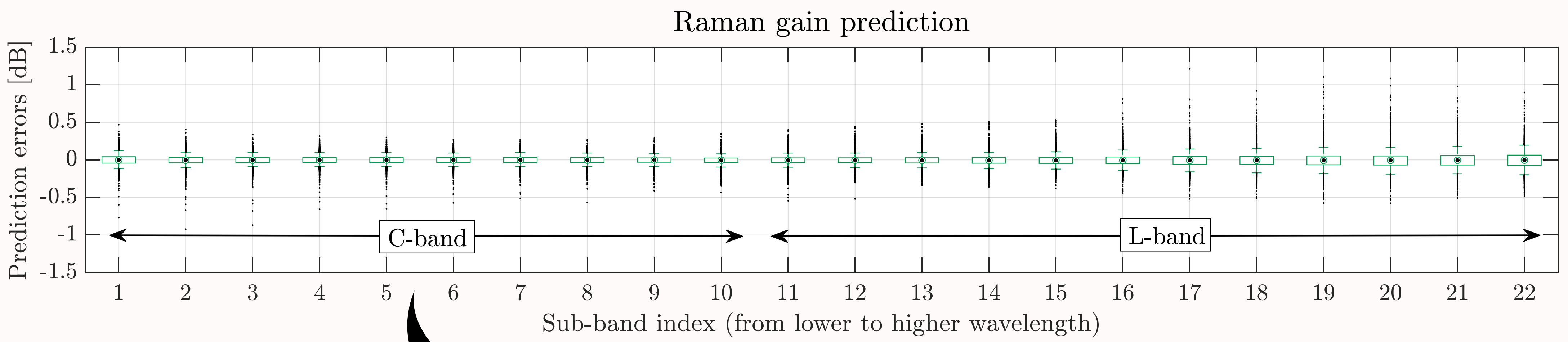



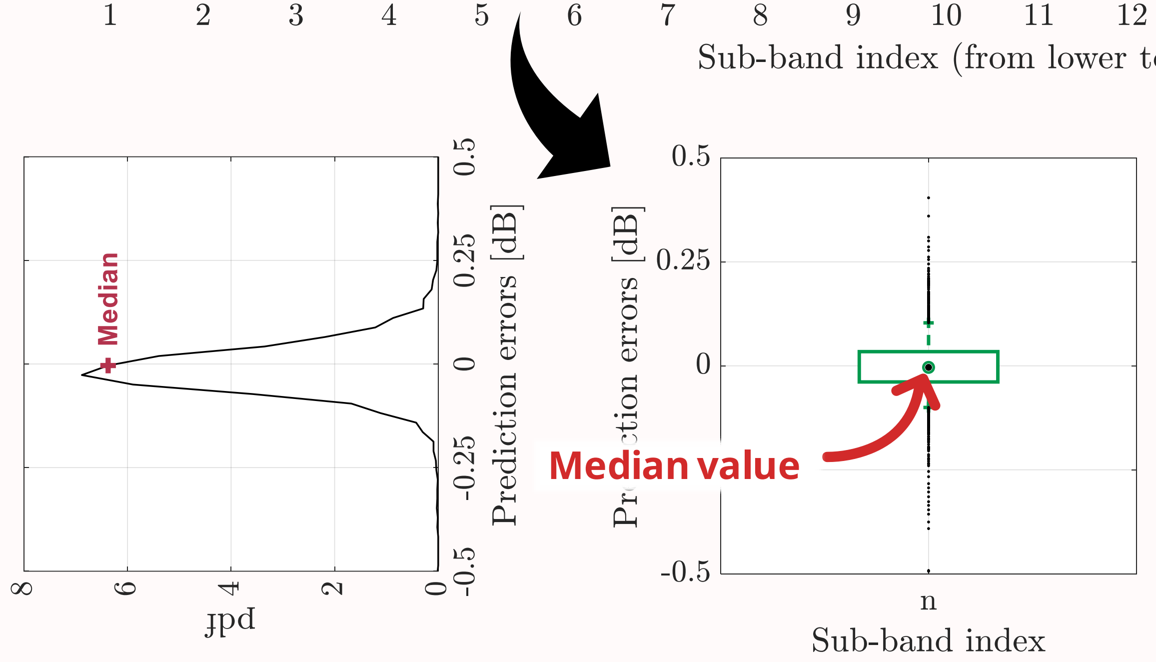

**LA-NN**



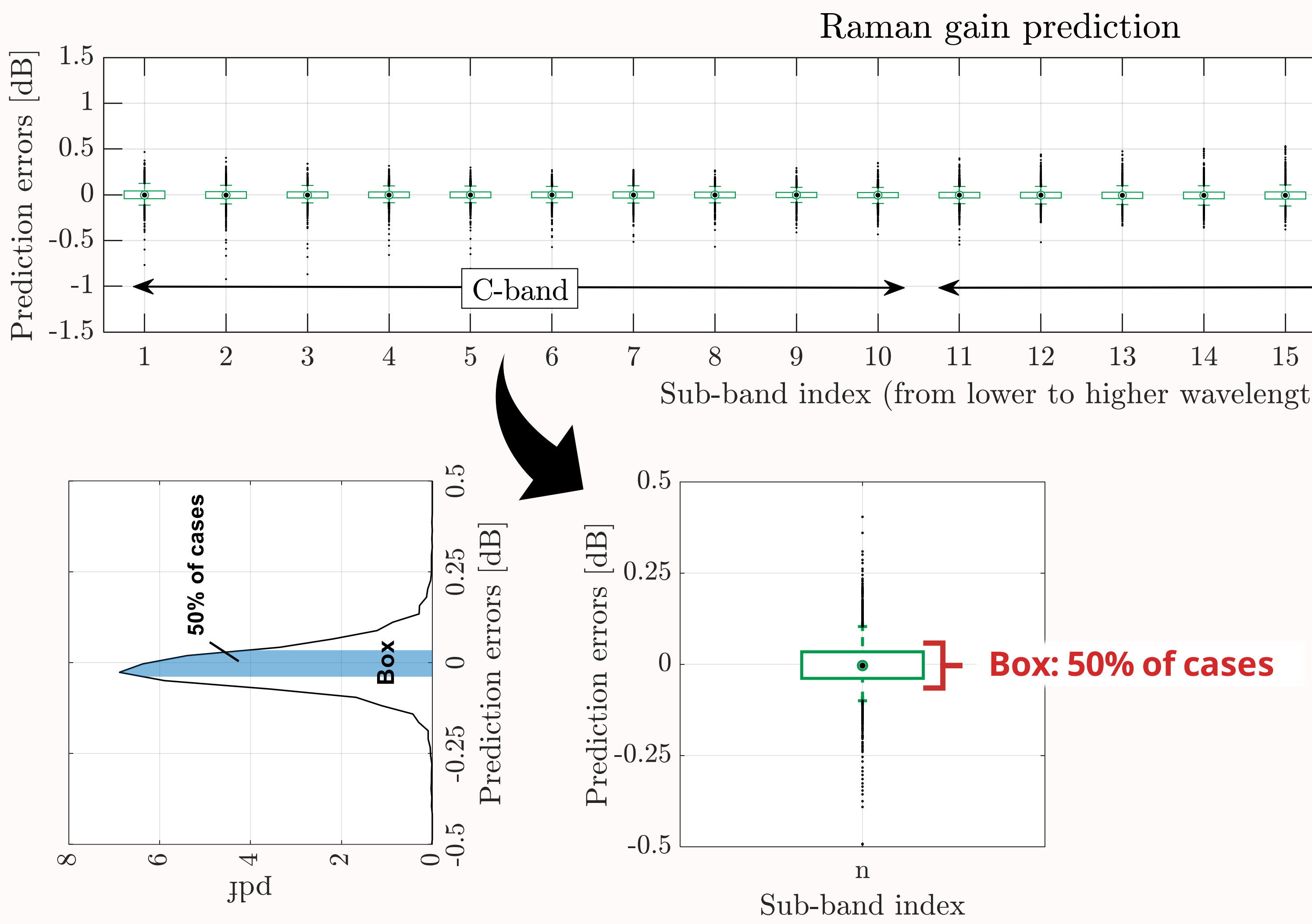



# Testing Results: LA-NN performance vs sub-band spectral occupation

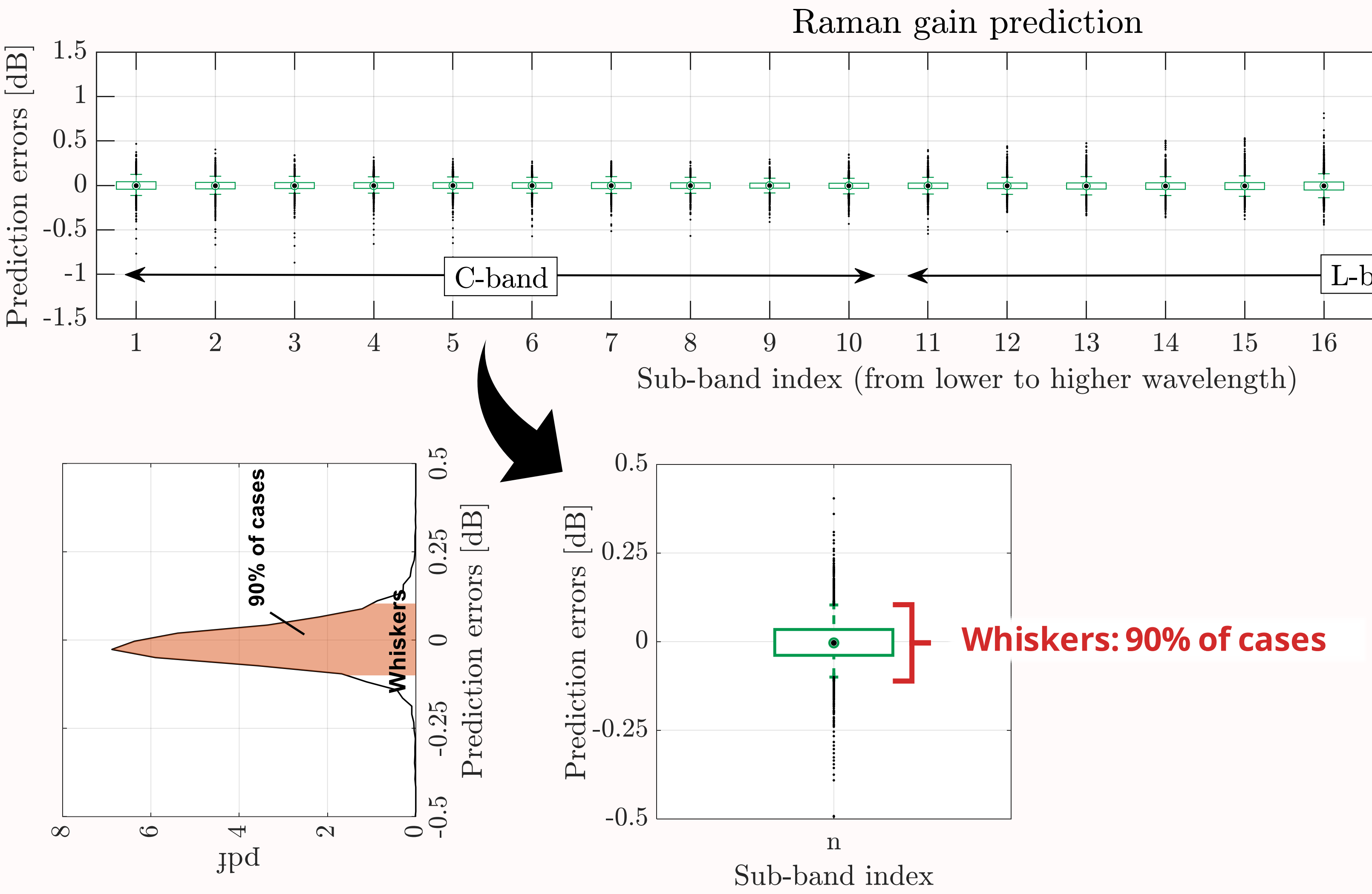


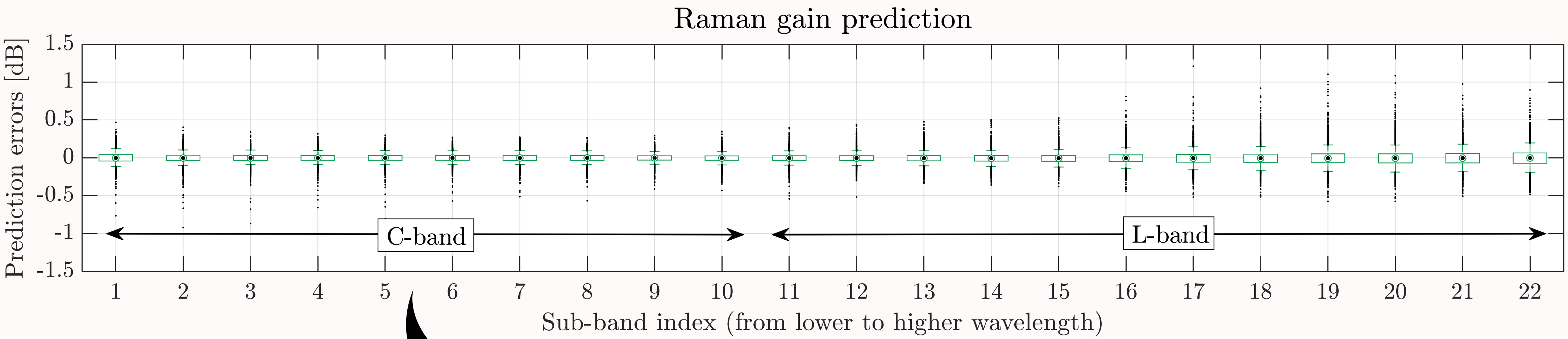
# Testing Results: LA-NN performance vs sub-band spectral occupation

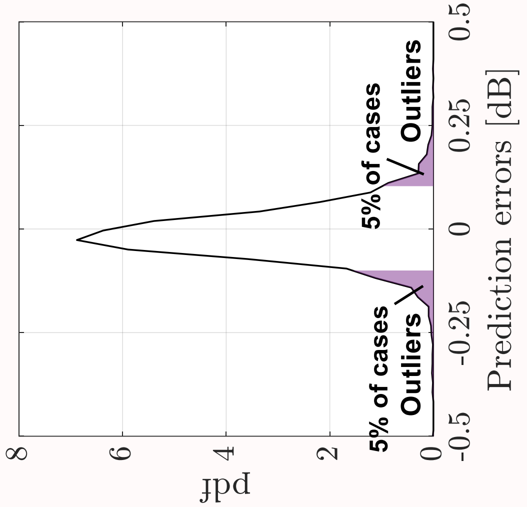


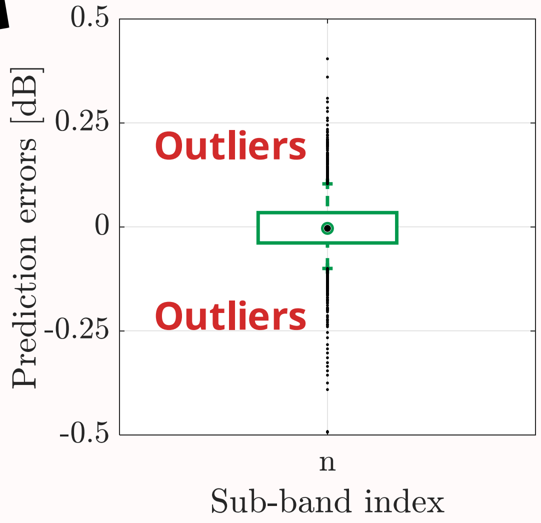
# Testing Results: LA-NN performance vs sub-band spectral occupation



# Testing Results: LA-NN performance vs sub-band spectral occupation

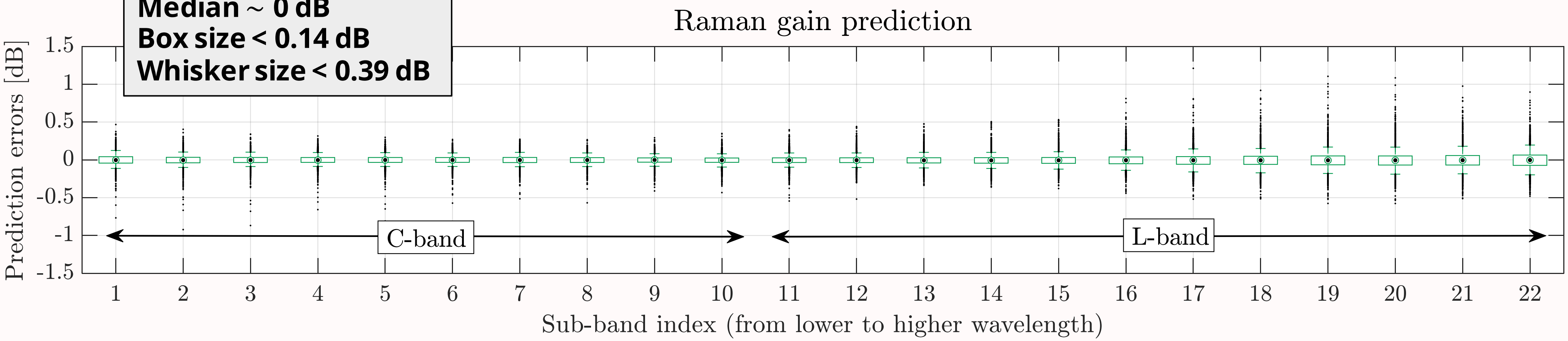


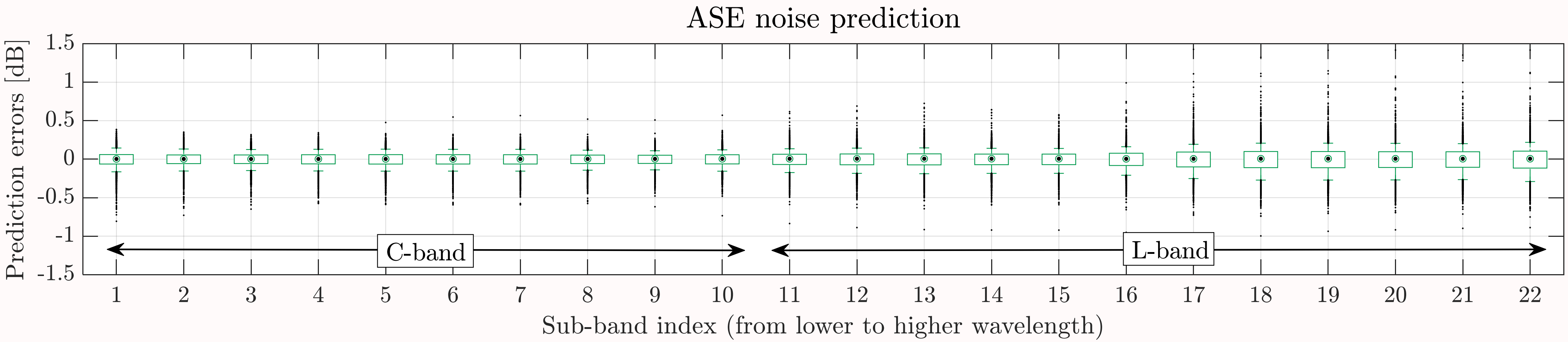



# Testing Results: LA-NN performance vs sub-band spectral occupation

**Median ~ 0 dB**
**Box size < 0.14 dB**
**Whisker size < 0.39 dB**



# Conclusions

- Several works have shown that ML is a promising, ultra-fast and highly accurate tool for the design of Raman amplifiers, in particular in a multi-band scenario
- Moreover, when moving towards multi-band transmissions (in our case C+L band), partial loads may have non-negligible impact on Raman amplification gain and ASE noise profiles due to ISRS
- ML can be also used for ultra-fast and highly accurate predictions of gain and noise profiles
  - In case of partial loads a LA-NN is necessary to take into account the different spectral loads

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# References - I


- B. Neto, A. L. J Teixeira, N. Wada, and P. S. André, "Efficient use of hybrid Genetic Algorithms in the gain optimization of distributed Raman amplifiers," Opt. Express 15, 17520-17528 (2007)
- G. C. M. Ferreira, S. P. N. Cani, M. J. Pontes and M. E. V. Segatto, "Optimization of Distributed Raman Amplifiers Using a Hybrid Genetic Algorithm With Geometric Compensation Technique," in *IEEE Photonics Journal*, vol. 3, no. 3, pp. 390-399, June 2011, doi: 10.1109/JPHOT.2011.2140366.
- Jing Chen et al 2018 J. Opt. **20** 025702, https://doi.org/10.1088/2040-8986/aaa2a6
- M. Ionescu, "Machine Learning for Ultrawide Bandwidth Amplifier Configuration," *2019 21st International Conference on Transparent Optical Networks (ICTON)*, Angers, France, 2019, pp. 1-4, doi: 10.1109/ICTON.2019.8840453.
- D. Zibar, A. M. Rosa Brusin, U. C. de Moura, F. Da Ros, V. Curri and A. Carena, "Inverse System Design Using Machine Learning: The Raman Amplifier Case," in *Journal of Lightwave Technology*, vol. 38, no. 4, pp. 736-753, 15 Feb.15, 2020, doi: 10.1109/JLT.2019.2952179.
- Yufeng Chen, Jiangbing Du, Yuting Huang, Ke Xu, and Zuyuan He, "Intelligent gain flattening in wavelength and space domain for FMF Raman amplification by machine learning based inverse design," Opt. Express 28, 11911-11920 (2020)
- G. Marcon, A. Galtarossa, L. Palmieri and M. Santagiustina, "Model-aware Deep Learning Method for Raman Amplification in Few-Mode Fibers," in *Journal of Lightwave Technology*, doi: 10.1109/JLT.2020.3034692.
- G. Borraccini et al., "Softwarized and Autonomous Raman Amplifiers in Multi-Band Open Optical Networks," *2020 International Conference on Optical Network Design and Modeling (ONDM)*, Castelldefels, Barcelona, Spain, 2020, pp. 1-6, doi: 10.23919/ONDM48393.2020.9133036.
- D. Zibar, A. Ferrari, V. Curri and A. Carena, "Machine Learning-Based Raman Amplifier Design," *2019 Optical Fiber Communications Conference and Exhibition (OFC)*, San Diego, CA, USA, 2019, pp. 1-3.

# References – II


- A. M. Rosa Brusin, V. Curri, D. Zibar and A. Carena, "An ultra-fast method for gain and noise prediction of Raman amplifiers," *45th European Conference on Optical Communication (ECOC 2019)*, Dublin, Ireland, 2019, pp. 1-4, doi: 10.1049/cp.2019.0976.
- U. C. de Moura, F. Da Ros, A. M. Rosa Brusin, A. Carena and D. Zibar, "Experimental Demonstration of Arbitrary Raman Gain-Profile Designs using Machine Learning," *2020 Optical Fiber Communications Conference and Exhibition (OFC)*, San Diego, CA, USA, 2020, pp. 1-3.
- A. M. Rosa Brusin, U. C. de Moura, A. D'Amico, V. Curri, D. Zibar and A. Carena, "Load Aware Raman Gain Profile Prediction in Dynamic Multi-Band Optical Networks," *2020 Optical Fiber Communications Conference and Exhibition (OFC)*, San Diego, CA, USA, 2020, pp. 1-3.
- A. M. Rosa Brusin, U. C. de Moura, V. Curri, D. Zibar and A. Carena, "Introducing Load Aware Neural Networks for Accurate Predictions of Raman Amplifiers," in *Journal of Lightwave Technology*, vol. 38, no. 23, pp. 6481-6491, 1 Dec.1, 2020, doi: 10.1109/JLT.2020.3014810.
- U. C. de Moura, F. Da Ros, A. M. Rosa Brusin, A. Carena and D. Zibar, "Experimental characterization of Raman amplifier optimization through inverse system design," in *Journal of Lightwave Technology*, doi: 10.1109/JLT.2020.3036603.
- U. C. De Moura, M. A. Iqbal, M. Kamalian, L. Krzczanowicz, F. Da Ros, A. M. Rosa Brusin, A. Carena, Wladek Forysiak, Sergei Turitsyn and D. Zibar, "Multi-band programmable gain Raman amplifier," in *Journal of Lightwave Technology*, doi: 10.1109/JLT.2020.3033768.